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Polymetallic Massive Sulphides and Cobalt-Rich Ferromanganese Crusts: *Status and Prospects*



ISA Technical Study: No. 2

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Polymetallic Massive Sulphide Deposits at the Modern Seafloor and their Resource Potential

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Polymetallic Massive Sulphide Deposits at the modern Seafloor and their Resource Potential

Since 1979, polymetallic massive sulphide deposits have been found at water depths up to 3,700 m in a variety of tectonic settings at the modern seafloor including mid-ocean ridges, back-arc rifts, and seamounts. Many of the sulphide deposits consist of a black smoker complex on top of a sulphide mound which commonly is underlain by a stockwork zone. It has been widely established that circulating seawater which is modified in a reaction zone close to a subaxial magma chamber is the principal carrier of metals and sulphur which are leached out of the oceanic basement. Precipitation of massive and stockwork sulphides at and beneath the seafloor takes place in response to mixing of the high-temperature (up to 400°C) metal-rich hydrothermal seawater fluid with ambient seawater. Polymetallic seafloor sulphide deposits can reach a considerable size (up to 100 million tonnes) and often carry high concentrations of copper (chalcopyrite), zinc (sphalerite), and lead (galena) in addition to gold and silver. Extremely high concentrations of gold have recently been found in a new type of seafloor mineral deposit previously only known as epithermal (magmatic) gold deposits on the continents. Due to the high concentration of base and precious metals, seafloor polymetallic sulphide deposits have recently attracted the interest of the international mining industry. The recovery of those deposits appears to be both economically and environmentally feasible due to certain advantages over land-based deposits and will likely become reality within this decade. For logistical and technical reasons, future mining operations will largely focus on deposits in national rather than international waters.

1. INTRODUCTION

The discovery of high-temperature black smokers, massive sulphides, and vent biota at the crest of the East Pacific Rise at 21°N in 1979^{1,2} confirmed that the formation of new oceanic crust through seafloor spreading is intimately associated with the generation of metallic mineral deposits at the seafloor. It was documented that the 350°C hydrothermal fluids discharging from the black smoker chimneys at this site at a water depth of about 2,600 m continuously precipitate metal sulphides in response to mixing of the high-temperature hydrothermal fluids with ambient seawater. The metal sulphides including pyrite, sphalerite, and chalcopyrite eventually accumulate at and just below the seafloor and have the potential to form a massive sulphide deposit. It has also been documented that circulation of seawater through the oceanic crust is the principal

process responsible for the formation of massive sulphide deposits in this environment. Seawater which deeply penetrates into the oceanic crust at seafloor spreading centres is being modified to a hydrothermal fluid with low pH, low Eh, and high temperature during water-rock interaction above a high-level magma chamber. This fluid is then capable of leaching and transporting metals and other elements which eventually precipitate as massive sulphides at the seafloor or as stockwork and replacement sulphides in the sub-seafloor. The resulting massive sulphide deposits can reach considerable size ranging from several thousand to about 100 million tonnes. High concentrations of base (copper, zinc, lead) and in particular precious metals (gold, silver) in some of these deposits have recently attracted the interest of the international mining industry.

In the two decades since the discovery of hydrothermal vents at the mid-ocean ridges, significant mineral deposits have been documented in more than a dozen different volcanic and tectonic settings around the world at water depths up to 3,700 m. Polymetallic sulphide deposits are found on fast-, intermediate-, and slow-spreading mid-ocean ridges, on axial and off-axis volcanoes and seamounts, in sedimented rifts adjacent to continental margins, and in subduction-related arc and back-arc environments (*Figs. 1 and 2*).

Land-based massive sulphide deposits and polymetallic sulphides at the seafloor are products of the same geological and geochemical processes and many analogies can be drawn between modern examples and base metal deposits currently being mined on land^{3,4,5,6,7}. Detailed geological, mineralogical, and geochemical analyses of massive sulphides from back-arc spreading centres of the western and south-western Pacific have indicated that these subduction-related sites represent the closest modern analogues of the majority of the economically important land-based deposits which occur in felsic volcanic rocks instead of mid-ocean ridge basalts⁸. Modern seafloor hydrothermal systems are thus excellent natural laboratories for understanding the genesis of volcanic-hosted massive sulphide deposits, and this knowledge can be translated directly to the ancient geological record on land, where evidence for the origin and nature of mineral deposits is often obscured by millions of years of geological history.

2. GEOLOGIC SETTING

Following the discovery of black smokers at the East Pacific Rise, there was a rapid growth in the number of hydrothermal deposits found on fast-spreading mid-ocean ridges. So many deposits were found along fast-spreading segments of the East Pacific Rise, and virtually nowhere else, that it became widely accepted that slower-spreading ridges could not support productive hydrothermal activity.

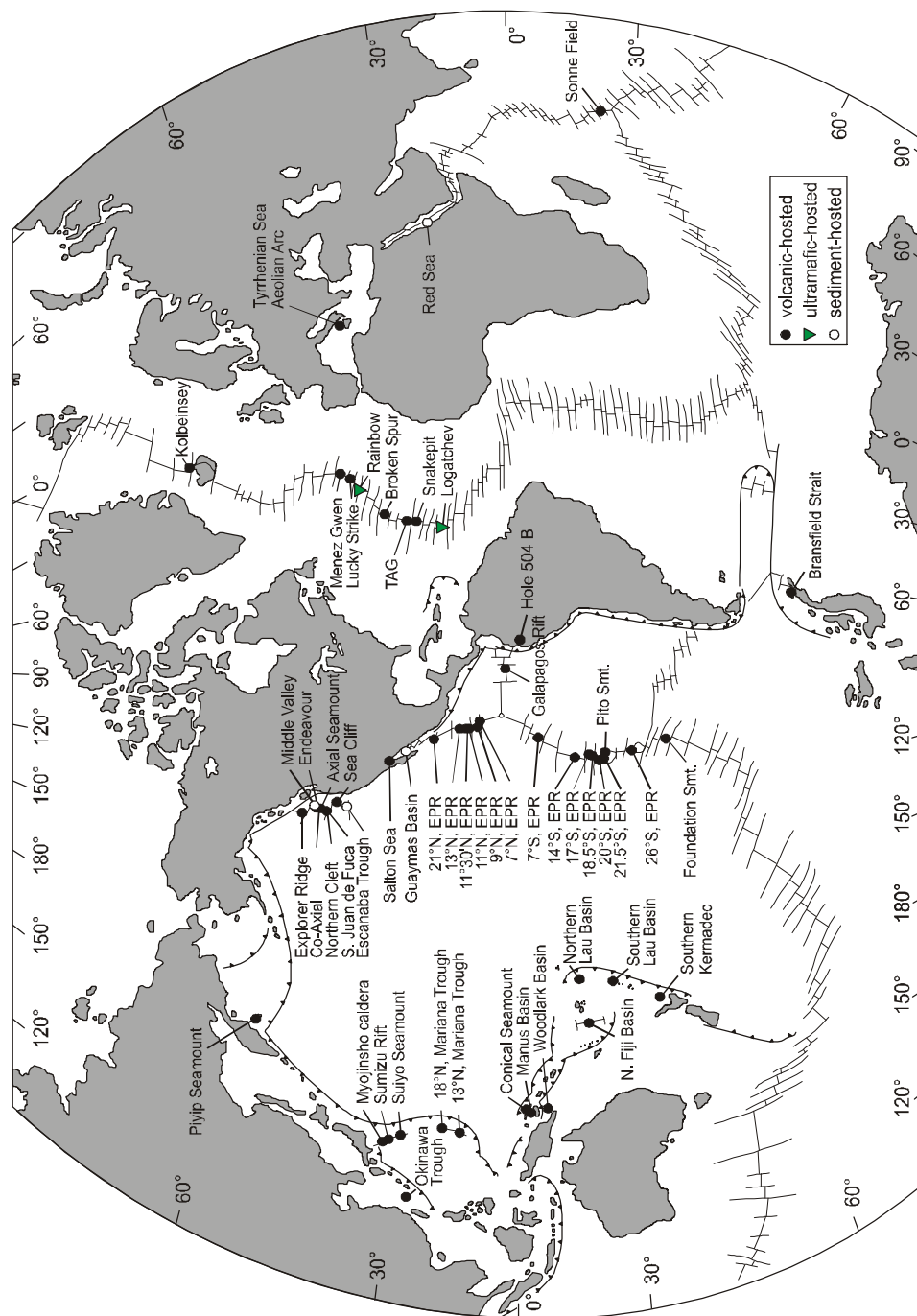


Figure 1. Location of hydrothermal systems and polymetallic massive sulphide deposits at the modern seafloor.

However, in 1985, the discovery of black smokers in the large TAG hydrothermal field at the Mid-Atlantic Ridge⁹ offered compelling evidence that slow-spreading ridges may also be important settings for sulphide deposits. This idea has since been confirmed by the discovery of a number of further large sulphide occurrences along the Mid-Atlantic Ridge (Logatchev, Snakepit, Broken Spur, Lucky Strike, Menez Gwen^{10,11,12,13}) and the Central Indian Ridge (Sonne Field^{14,15,16}).

Shortly after the discovery at 21°N, large sulphide deposits were also discovered in sediment-filled basins in the Gulf of California (Guaymas Basin¹⁷). The idea that sedimented ridges might also be important sites for sulphide accumulation was confirmed in 1991 and 1996, when the Ocean Drilling Program intersected about 100 m of massive sulphides in the large Middle Valley deposit on the Juan de Fuca Ridge off-shore Canada^{18,19}.

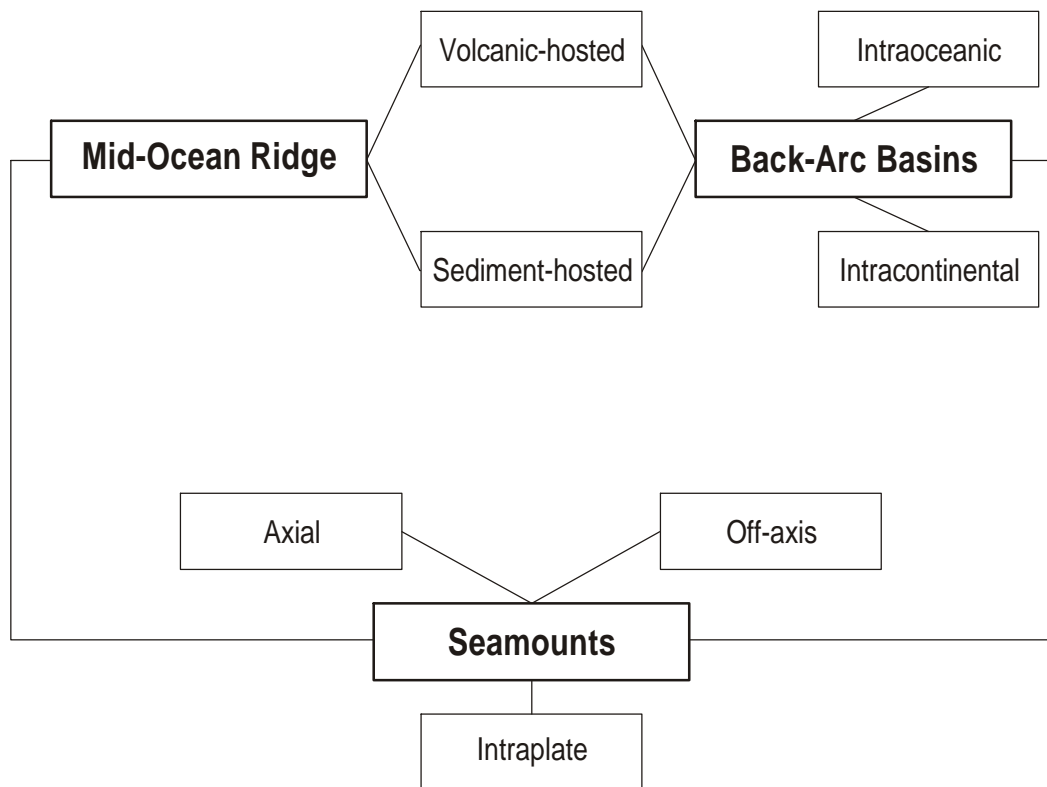


Figure 2. Simplified diagram showing the diverse geological environments for the occurrence of seafloor hydrothermal systems. Polymetallic massive sulphide deposits have been found in all settings except for intraplate seamounts.

The first sulphide deposits reported in back-arc spreading centres were found in the Central Manus Basin²⁰ and the Mariana Trough^{21,22}. These discoveries led to extensive exploration of the marginal basins and the arc and back-arc systems of the western and southwestern Pacific in the late 1980s. The complex volcanic and tectonic settings of convergent margins in the Pacific suggested that a number of different deposit types might be present in this region. A wide range of mineral deposits have since been found in back-arc rifts at different stages of opening (immature versus mature), on volcanoes along the active volcanic fronts of the arcs, as well as in rifted fore-arc environments. Well-known examples of polymetallic massive sulphide deposits have been described from mature back-arc spreading centres such as the North Fiji Basin²³, along propagating back-arc rifts such as the Valu Fa Ridge in the southern Lau Basin²⁴, and in nascent back-arc rifts such as the Okinawa Trough²⁵. In 1991, extensive sulphide deposits were found to be associated with felsic volcanism in the Eastern Manus Basin²⁶, and hydrothermal deposits have also been located in the western Woodlark Basin, where seafloor spreading propagates into the continental crust of Papua New Guinea²⁷. Today, more than 100 sites of hydrothermal mineralisation are known at the modern seafloor^{28,29,30} including at least 25 sites with high-temperature (350-400°C) black smoker venting.

The majority of sites so far have been located at the East Pacific Rise, the Southeast Pacific Rise, and the Northeast Pacific Rise, mainly because the first discovery of an active high-temperature hydrothermal system was made at 21°N at the East Pacific Rise off shore Baja California. Only one site has so far been located at the ridge system of the Indian Ocean, close to the Rodriguez Triple Junction^{14,15,16}. The scarcity of sulphide deposits on the Mid-Atlantic Ridge and in the Indian Ocean is, at least to a large extent, a function of restricted exploration activity in these areas. It has been assumed that today only about 5% of the 60,000 km of oceanic ridges worldwide have been surveyed and investigated in some detail.

3. HYDROTHERMAL CONVECTION

At oceanic spreading centres, seawater penetrates deeply into the newly formed oceanic crust along cracks and fissures, which are a response to thermal contraction and seismic events typical for zones of active seafloor spreading. The seawater circulating through the oceanic crust at seafloor spreading centres is converted into an ore-forming hydrothermal fluid in a reaction zone which is situated close to the top of a subaxial magma chamber (*Fig. 3*). Major physical and chemical changes in the circulating seawater include (i) increasing temperature, (ii) decreasing pH, and (iii) decreasing Eh.

The increase in temperature from about 2°C to values >400°C^{31,32} is a result of conductive heating of a small percentage of seawater close to the solidified top of a high-

level magma chamber³³. This drives the hydrothermal convection system and gives rise to black smokers at the seafloor. High-resolution seismic reflection studies have indicated that some of these magma reservoirs may occur only 1.5-3.5 km below the seafloor^{34,35}. The crustal residence time of seawater in the convection system has been constrained to be 3 years or less³⁶. Data from water/rock interaction experiments indicate that, with increasing temperatures, the Mg^{2+} dissolved in seawater (about 1,280 ppm) combines with OH-groups (which originate from the dissociation of seawater at higher temperatures) to form $Mg(OH)_2$, which is incorporated in secondary minerals such as smectite (<200°C) and chlorite (>200°C)^{37,38,39,40}. The removal of OH-groups creates an excess of H^+ ions, which is the principal acid-generating reaction responsible for the drop in pH from seawater values (pH 7.8 at 2°C) to values as low as pH 2⁴¹. Exchange of H^+ for Ca^{2+} and K^+ in the rock releases these elements into the hydrothermal fluid.

The leaching of Ca^{2+} balances the continuous removal of Mg^{2+} from seawater. Endmember hydrothermal fluids are defined as presumed deep-seated high-temperature fluids computed by extrapolating compositions and physical parameters back to $Mg=0$ on the assumption of quantitative removal of Mg. At high temperatures, however, the formation of epidote (Ca fixation) also results in an excess of H^+ which further contributes to the acidity of the hydrothermal fluid. These reactions take place at water/rock ratios of less than five and commonly close to one⁴². The oxygen which is present in the circulating seawater in the form of sulphate is removed partly by precipitation of anhydrite and partly through conversion of igneous pyrrhotite to secondary pyrite and the oxidation of Fe^{2+} to Fe^{3+} forming Fe-oxyhydroxides and secondary magnetite in the basalt⁴⁰. Partial reduction of seawater SO_4^{2-} contributes to the formation of H_2S , but most of the reduced S in the fluid is derived from the rock itself.

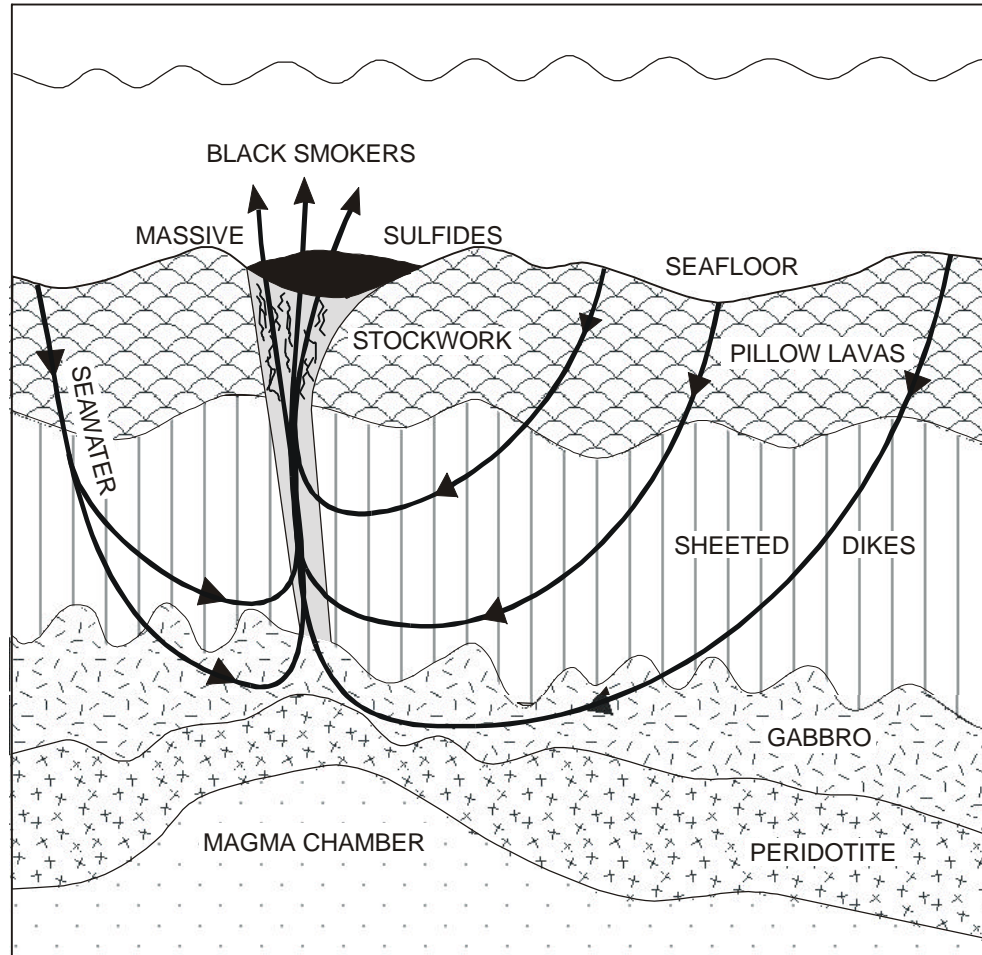


Figure 3. Model showing a seawater hydrothermal convection system above a subaxial magma chamber at an oceanic spreading centre. Radius of a typical convection cell is about 3-5 km. Depth of the magma chamber usually varies from 1.5-3.5 km.

This highly corrosive fluid is now capable of leaching elements such as Li, K, Rb, Ca, Ba, the transition metals Fe, Mn, Cu, Zn, together with Au, Ag and some Si from the oceanic basement⁴³. Sulphide droplets in the basalt are considered to be the major source for metals and S⁴⁴. The metals are mainly transported as chloride complexes at high temperatures and, in some cases, as bisulphide complexes (in particular Au) at lower temperatures.

Due to its increased buoyancy at high temperatures, the hydrothermal fluid rises rapidly from the deep-seated reaction zone to the surface along major faults and fractures within the rift valley or close to the flanks of the rift. In particular the intersections of

faults running parallel and perpendicular to the ridge axis are the loci of high-velocity discharge black smokers and massive sulphide mounds. The sulphide precipitation within the upflow zone (stockwork) and at the seafloor (massive sulphides) is a consequence of changing physical and chemical conditions during mixing of high-temperature (250-400°C), metal-rich hydrothermal fluids with cold (about 2°C), oxygen-bearing seawater (Fig. 4).

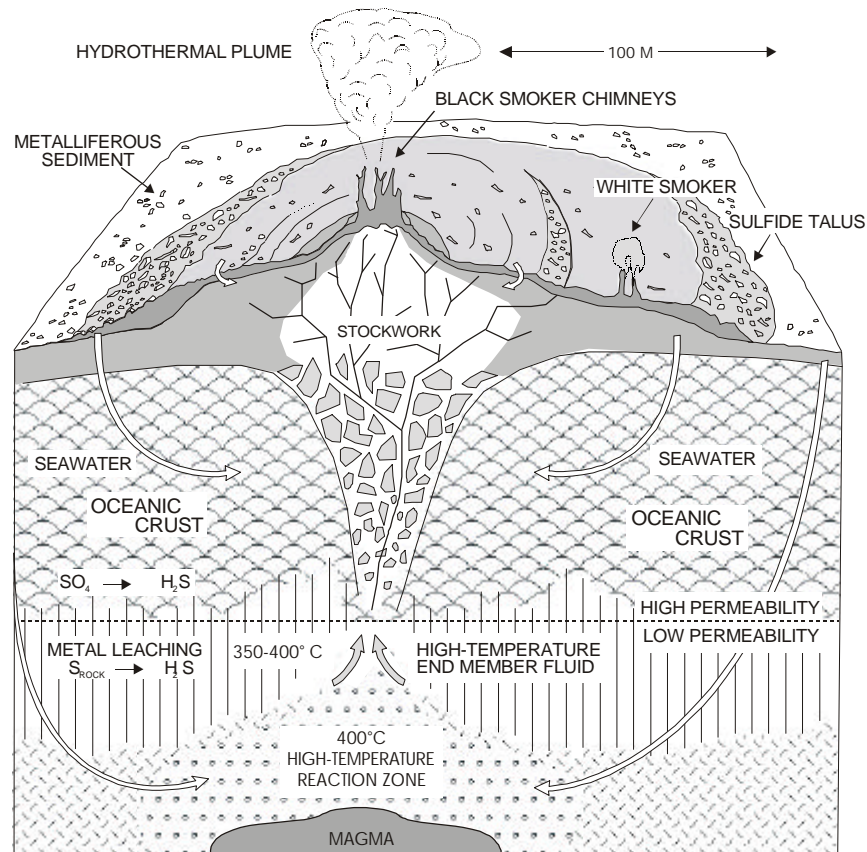


Figure 4. Cross-section showing the principal components of a seafloor hydrothermal system.

4. MINERALOGY

The mineralogy of seafloor sulphide deposits (*Table 1*) has been documented in a number of detailed studies of samples from various sites^{22,45,46,47,48,49,50,51,52}. The mineral paragenesis of sulphide deposits at volcanic-dominated mid-ocean ridges usually includes assemblages that formed at temperatures ranging from about 300-400°C to less than 150°C. High-temperature fluid channels of black smokers and the interiors of

sulphide mounds commonly consist of pyrite and chalcopyrite together with pyrrhotite, isocubanite, and locally bornite.

The outer portions of chimneys and mounds are commonly composed of lower temperature precipitates such as sphalerite/wurtzite, marcasite, and pyrite, which are also the principal sulphide minerals of low-temperature white smoker chimneys. Anhydrite is important in the high-temperature assemblages, but is typically replaced by later sulphides, amorphous silica, or barite at lower temperatures.

Sulphide mineralisation at back-arc spreading centres has some mineralogical characteristics that are similar to hydrothermal precipitates at volcanic-dominated mid-ocean ridges. Commonly, pyrite and sphalerite are the dominant sulphides. Chalcopyrite is common in the higher temperature assemblages, but pyrrhotite is rare. Barite and amorphous silica are the most abundant non-sulphides.

Many of the deposits forming in back-arc rifts are characterised by a variety of minor and trace minerals such as galena, tennantite, tetrahedrite, cinnabar, realgar, orpiment, and complex, non-stoichiometric Pb-As-Sb sulphosalts. The first examples of visible primary gold in seafloor sulphides were documented in samples of lower temperature (<300°C) white smoker chimneys from the southern Lau Basin^{53,54} and occur as coarse-grained (18 microns) co-depositional inclusions in massive, Fe-poor sphalerite.

Table 1. Mineralogical Composition of Seafloor Polymetallic Sulphide Deposits

	Back-Arc Deposits	Mid-Ocean Ridge Deposits
Fe-sulphides	pyrite, marcasite, pyrrhotite	pyrite, marcasite, pyrrhotite
Zn-sulphides	sphalerite, wurtzite	sphalerite, wurtzite
Cu-sulphides	chalcopyrite, isocubanite	chalcopyrite, isocubanite
silicates	amorphous silica	amorphous silica
sulphates	anhydrite, barite	anhydrite, barite
Pb-sulphides	galena, sulphosalts	
As-sulphides	orpiment, realgar	
Cu-As-Sb-sulphides	tennantite, tetrahedrite	
native metals	gold	

5. METAL CONTENTS

Despite moderate tonnages in several seafloor deposits, recovered samples from about 50 deposits worldwide represent no more than a few hundred tonnes of material. Based on existing data and lacking information on the third dimension it is premature to comment on the economic significance of seafloor massive sulphides. Published analyses of sulphide samples, however, indicate that these deposits may contain important concentrations of metals that are comparable to those found in ores from massive

sulphide mines on land. Estimated concentrations of base metals in seafloor massive sulphides tend to be higher, which in part may be due to a strong bias in sampling.

A large number of seafloor sulphides are recovered during submersible operations. A bias in the analytical data arises, because sulphide chimneys which are relatively easy to sample are often the focus of study. However, they are unlikely to be representative of the bulk composition of the deposits as a whole (e.g., 11 analysed samples from the Southern Juan de Fuca site have an average Zn content of greater than 34 wt.%) and little is known about the interiors of larger sulphide mounds and the underlying stockwork zones. Systematic sampling of both high- and low-temperature assemblages across the surfaces of some large active areas (e.g., TAG hydrothermal field, Explorer Ridge, Galapagos Rift) are more representative of the range of sulphide precipitates which comprise large deposits. Sufficient sampling, which has led to potentially realistic estimates of metal concentrations, has been achieved at only a few sites (e.g., Middle Valley, Explorer Ridge, Galapagos Rift) while quantitative assessment of contained metals has been possible only for the Atlantis II Deep in the Red Sea. Adequate information about the continuity of base and precious metal concentrations in the interiors of the deposits can only be provided by drilling, as successfully demonstrated at the TAG mound (Ocean Drilling Program Leg 158⁵⁵) and the Middle Valley site (Ocean Drilling Program Leg 139¹⁸, Ocean Drilling Program Leg 169⁵⁶).

Comparison of close to 1,300 chemical analyses of seafloor sulphides reveals systematic trends in bulk composition between deposits in different volcanic and tectonic settings (*Table 2*). The sediment-hosted massive sulphides (e.g., Escanaba Trough, Guaymas Basin), while being somewhat larger than deposits at the bare-rock mid-ocean ridges, appear to have lower concentrations and different proportions of base metals. Massive sulphides from these deposits average 4.7 wt.% Zn, 1.3 wt.% Cu, and 1.1 wt.% Pb (n=57). This reflects the influence of thick sequences of turbidite sediments on hydrothermal fluids ascending to the seafloor and the tendency for widespread precipitation of metals beneath the sediment-seawater interface. Calcite, anhydrite, barite, and silica are major components of the hydrothermal precipitates and may significantly dilute the base metals in sediment-hosted deposits. On basaltic, sediment-free mid-ocean ridges, sulphides are precipitated largely around the vent site, resulting in smaller deposits, but higher concentrations of metals. The largest deposits for which there are representative suites of samples (e.g., Explorer Ridge, Endeavour Ridge, Axial Seamount, Cleft Segment, East Pacific Rise, Galapagos Rift, TAG, Snakepit) have a narrow range of metal concentrations, and average 8.5 wt.% Zn and 4.8 wt.% Cu, but have only low concentrations (0.1 wt.%) of Pb (n=1,259, *Table 2*). Anhydrite, barite, and silica are important constituents of some chimneys, but on average they account for <20 % of the samples analysed.

Vent fluid compositions at all of the bare-rock mid-ocean ridge sites are remarkably similar, reflecting the high-temperature reaction of seawater with a uniform

basaltic crust at greenschist facies conditions^{57,58,59}. Therefore, large variations in base metal concentrations between deposits on the mid-ocean ridges likely reflect a sampling bias or differences in the conditions of formation of the deposits. For example, zinc-rich deposits at Axial Seamount and the Southern Juan de Fuca site appear to have formed at lower average temperatures (<300°C) than Cu-rich deposits (>300°C) elsewhere at the mid-ocean ridges.

Relative to samples from sediment-starved mid-ocean ridges, massive sulphides forming in basaltic to andesitic environments of intraoceanic back-arc spreading centres (e.g., Mariana Trough, Manus Basin, North Fiji Basin, Lau Basin) are characterised by elevated average concentrations of Zn (16.5 wt.%), Pb (0.4 wt.%), and Ba (12.6 wt.%), but low contents of Fe (13.0 wt.%, n=573, Table 2). Polymetallic sulphides in the Okinawa Trough, where rhyolites and dacites are a product of back-arc rifting in continental crust, have low Fe contents (6.2 wt.%) but are enriched in Zn (20.2 wt.%) and Pb (11.8 wt.%), and have high concentrations of Ag (2,304 ppm, maximum 1.1 wt.%), As (1.8 wt.%), and Sb (0.7 wt.%, n=40, Table 2). High Sb and As contents are accounted for by the presence of tetrahedrite, stibnite, and As-sulphides (i.e., realgar and orpiment) in these assemblages.

Table 2. Bulk Chemical Composition of Seafloor Polymetallic Sulphides

Element	Intraoceanic Back-Arc Ridges	Intracontinental Back-Arc Ridges	Mid-Ocean Ridges
Pb (wt.%)	0.4	11.8	0.1
Fe	13.0	6.2	26.4
Zn	16.5	20.2	8.5
Cu	4.0	3.3	4.8
Ba	12.6	7.2	1.8
As (ppm)	845	17,500	235
Sb	106	6,710	46
Ag	217	2,304	113
Au	4.5	3.1	1.2
(N)	573	40	1,259

The bulk composition of seafloor sulphide deposits in various tectonic settings is a consequence of the nature of the volcanic source rocks from which the metals are leached. Potential source rocks identified in the different tectonic environments range from MORB and clastic sediments at the mid-ocean ridges, to lavas of bimodal composition (andesite, basalt) in intraoceanic back-arcs and felsic volcanics (dacite, rhyolite) which are typical for young intracontinental back-arc rifts. These compositional variations are reflected by differences in the composition of the respective vent fluids. For example, chemical analyses of endmember fluids from the Vai Lili hydrothermal field which occurs in andesites of the Valu Fa Ridge in the southern Lau Basin indicate much

higher concentrations of Zn, Pb, As and other elements compared to typical mid-ocean ridge fluids. Massive sulphides from the Okinawa Trough²⁵ are even more enriched in Pb than massive sulphides from the Lau Basin, which is likely a consequence of the high Pb contents of rhyolites and andesites in the source region and the characteristics of the hydrothermal fluids generated in this environment. High Pb and Ba contents of sediment-hosted seafloor sulphides simply reflect the elevated Pb and Ba contents of individual components in the sediment (e.g., feldspar). Similar trends in the bulk composition of massive sulphide deposits are widely recognised in ancient terrains^{3,52,60}.

6. SIZE AND TONNAGE

Considering that estimates of the continuity of sulphide outcrop are difficult, and that the thickness of the deposits is commonly poorly constrained, estimates for several deposits on the mid-ocean ridges suggest a size of 1-100 million tonnes, although the depth extend of mineralisation is difficult to assess. The by far largest deposits are found on failed and heavily sedimented but still hydrothermally active oceanic ridges. Drilling carried out by the Ocean Drilling Program during Legs 139 and 169 at the sediment-covered Middle Valley deposit on the northern Juan de Fuca Ridge has indicated about 8-9 million tonnes of sulphide ore⁵⁶ (*Table 3*). During both legs, about 100 m of massive sulphides and 100 m of stockwork were drilled at the Bent Hill site. The sub-seafloor stockwork zone is underlain by a stratiform Cu-rich horizon (“deep copper zone”) with copper grades ranging up to 17 wt.% Cu⁵⁶. This significant discovery now represents an important new exploration target for the land-based mineral industry. The TAG hydrothermal mound located in 3,650 m water depth at the Mid-Atlantic Ridge 26°N was drilled during Ocean Drilling Program Leg 158 in 1994 to a total depth of 125 m^{55,61}. It was estimated that the active TAG mound contains about 2.7 million tonnes of sulphide ore above the seafloor and approximately 1.2 million tonnes of sulphides in the sub-seafloor stockwork⁶². A comparison of the size of the modern deposits with some of the ancient ore bodies and ore districts indicates that extremely large deposits such as Kidd Creek in Canada (135 million tonnes) or Neves Corvo in Portugal (262 million tonnes) so far have not been discovered at the modern seafloor.

The largest known marine sulphide deposit is still the Atlantis II Deep in the Red Sea, which was discovered more than ten years before the first black smoker at the East Pacific Rise⁶³. The Atlantis II Deep mineralisation largely consists of metalliferous muds, instead of massive sulphides, which is a consequence of the high salinity which the hydrothermal fluids acquire by circulation through thick Miocene evaporites at the flanks of the Red Sea rift. A detailed evaluation of the 40 km² deposit has indicated 94 million tonnes of dry ore with 2.0 wt.% Zn, 0.5 wt.% Cu, 39 ppm Ag, and 0.5 ppm Au^{64,65,66} which results in a total precious metal content of roughly 4,000 tonnes of Ag and

50 tonnes of Au. A pilot mining test at 2,000 m depth has shown that this deposit can be successfully mined.

Estimates of sizes between 1-100 million tonnes for individual massive sulphide deposits on the seafloor thus are well within the range of typical volcanic-associated massive sulphide deposits on land. However, most occurrences of seafloor sulphides amount to less than a few thousand tonnes, and consist largely of scattered hydrothermal vents and mounds usually topped by a number of chimneys with one or more large accumulations of massive sulphide. More than 60 individual occurrences have been mapped along an 8 km segment of Southern Explorer Ridge, but most of the observed mineralisation occurs in two large deposits with dimensions of 250 m x 200 m⁶⁷. The thicknesses of the deposits are difficult to determine unless their interiors have been exposed by local faulting. Typical black smokers are estimated to produce about 250 tonnes of massive sulphide per year. Thus, a local vent field with a few black smokers can easily account for a small size sulphide deposit, pending on the duration of activity. Reports of explored dimensions of deposits based on visual estimates from submersibles may be accurate to only +/-50% of the distances given and commonly include weakly mineralised areas between larger, discrete sulphide mounds (thereby over-estimating the continuity of sulphide outcrop). Reports based on transponder navigated camera tracks are probably accurate to +/-20%, but the extent of coverage is limited due to the slow tow-speeds and the narrow image. No geophysical tools currently provide a good basis for estimating the area of sulphide outcrop. High-resolution, deep-towed side-scan sonar may be refined to provide more accurate information over larger areas.

7. OCCURRENCE AND DISTRIBUTION OF GOLD

Gold grades are locally high in samples from a number of seafloor deposits at the mid-ocean ridges^{50,68,69,70}, and in particular in samples from the back-arc spreading centers⁵⁴. Average gold contents for deposits at the mid-ocean ridges range from <0.2 ppm Au up to 2.6 ppm Au, with an overall average of 1.2 ppm Au (n=1,259, *Table 5*). In volcanic-dominated, sediment-free deposits, high-temperature (350°C) black smoker chimneys composed of Cu-Fe-sulphides typically contain <0.2 ppm Au. Here, much of the gold is lost to a diffuse hydrothermal plume. The gold content of massive sulphides from the interior of hydrothermal mounds is supposed to be similar to the gold content of the high-temperature chimney assemblages. Higher concentrations of primary gold occur in lower-temperature (<300°C), sphalerite-dominated assemblages with sulphosalts and late-stage barite and amorphous silica at Axial Seamount (6.7 ppm Au^{68,70}). Comprehensive sampling of a few large, mature deposits at sediment-free ridges in the Northeast Pacific and Mid-Atlantic indicates typical average gold contents in the range of 1-2 ppm Au. Local enrichment of more than 40 ppm Au (TAG hydrothermal field⁷¹) is a consequence of remobilisation and reconcentration (hydrothermal reworking) of gold

during sustained venting of hydrothermal fluids through the sulphide mounds (i.e., zone refining).

Table 3. Gold Grades in Polymetallic Massive Sulfides from the Modern Seafloor

	Au (ppm)		(N)
	range	average	
Conical Seamount (PNG) magmatic-epithermal system	0.01 – 230.0	26.0	40
Immature Back-Arc Ridges (intermediate to felsic volcanics)			
Lau Basin	0.01-28.7	2.8	103
Okinawa Trough	0.01-14.4	3.1	40
Central Manus Basin	0.01-52.5	30.0	10
Eastern Manus Basin	1.30-54.9	15.0	26
Woodlark Basin	3.80-21.1	13.1	6
Mature Back-Arc Ridges (MOR-type volcanics)			
Mariana Trough	0.14- 1.7	0.8	11
North Fiji Basin	0.01-15.0	2.9	42
Mid-Ocean Ridges (MORB)	0.01-6.7	1.2	1,259

The gold contents of sulphides from deposits in sedimented rifts (e.g., Guaymas Basin) are typically <0.2 ppm Au. Here, the interaction of hydrothermal fluids with organic-rich sediments causes strongly reducing conditions which limit the amount of gold that can be transported in hydrothermal solutions. However, Cu-rich sulphides from the Escanaba Trough are an exception as they contain up to 10 ppm Au with an average of 1.5 ppm Au. This is likely explained by an enriched source in the underlying sediments^{72,73}. The metalliferous muds in the Atlantis II Deep have bulk gold contents of about 0.5 ppm Au⁶⁴, but sulphide-rich horizons have gold contents from <0.5 up to 4.6 ppm Au and average close to 2 ppm Au⁶⁶.

Polymetallic sulphides from a number of back-arc spreading centres have revealed particular high concentrations of gold averaging between 3-30 ppm Au⁵⁴. Gold appears to be most abundant in sulphides associated with immature seafloor rifts in continental or island arc crusts. These settings are dominated by calc-alkaline volcanics including andesites, dacites, and rhyolites (e.g., Okinawa Trough, Lau Basin, Manus Basin). Polymetallic sulphides from the Valu Fa Ridge in the Lau back-arc have gold contents of up to 29 ppm Au with an average of 2.8 ppm Au (n=103, *Table 3*). These

samples represent the first known examples of visible primary gold in polymetallic sulphides at active vents^{53,54}. In the Okinawa Trough, gold-rich sulphide deposits with up to 14 ppm Au (average 3.1 ppm, n=40) occur in a back-arc rift within continental crust and resemble Kuroko-type massive sulphides^{25,74,75}. Preliminary analyses of sulphides reported from the Central Manus Basin (Vienna Woods) indicate average gold contents of up to 30 ppm Au (n=10) and maximum concentrations of more than 50 ppm Au. The average gold content of massive sulphides in the Eastern Manus Basin (Pacmanus) is 15 ppm with a maximum of 54.9 ppm Au (n=26⁷⁶). High gold contents up to 21 ppm Au have been found in barite chimneys in the Western Woodlark Basin, where seafloor spreading propagates into continental crust off Papua New Guinea^{77,78}.

The most gold-rich seafloor deposit found to date is located at Conical Seamount in the territorial waters of Papua New Guinea close to Lihir Island. Maximum gold concentrations in samples collected from the summit plateau of this seamount (2.8 km basal diameter at 1,600 m water depth, top at 1,050 m) range up to 230 ppm with an average of 26 ppm for 40 samples analysed^{79,80}.

8. RESOURCE POTENTIAL OF SEAFLOOR SULPHIDE DEPOSITS

Out of the more than 200 sites of hydrothermal mineralisation currently known at the modern seafloor, only about 10 deposits may have sufficient size and grade to be considered for future mining, although information on the thickness of most of those sulphide deposits is not yet available (*Table 4*). These potential mine sites include the Atlantis II Deep in the Red Sea, Middle Valley, Explorer Ridge, Galapagos Rift, and the East Pacific Rise 13°N in the Pacific Ocean, the TAG hydrothermal field in the Atlantic Ocean, as well as the Manus Basin, the Lau Basin, the Okinawa Trough, and the North Fiji Basin in the western and south-western Pacific. All of these sites except two (East Pacific Rise 13°N and TAG hydrothermal field) are located in the Exclusive Economic Zones of coastal states including Saudi Arabia, Sudan, Canada, Ecuador, Papua New Guinea, Tonga, Japan, and Fiji. Scientific drilling so far has been carried out by the Ocean Drilling Program to a depth of 125 m at the TAG hydrothermal field and to about 200 m at Middle Valley. Leg 193 of the Ocean Drilling Program is scheduled for December/January 2000/2001 to explore the third dimension of the Eastern Manus Basin (Pacmanus site). The Atlantis II Deep is still the only deposit that has been evaluated by a commercial company (Preussag, Germany) in the late 1970s based on standards usually applied by the minerals industry to land-based ore deposits. A pilot mining test has successfully demonstrated that the metalliferous muds occurring below the surface of a 60°C brine not only in the Atlantis II Deep can be continuously mined^{81,82}.

Table 4. Possible Sites for Mining of Seafloor Massive Sulphide Deposits

Deposit	Ocean Area	Water Depth	Jurisdiction	Country
Atlantis II Deep	Red Sea	2,000-2,200 m	EEZ	Saudi Arabia, Sudan
Middle Valley	Northeast Pacific	2,400-2,500 m	EEZ	Canada
Explorer Ridge	Northeast Pacific	1,750-2,600 m	EEZ	Canada
Lau Basin	Southwest Pacific	1,700-2,000 m	EEZ	Tonga
North Fiji Basin	Southwest Pacific	1,900-2,000 m	EEZ	Fiji
Eastern Manus Basin	Southwest Pacific	1,450-1,650 m	EEZ	Papua New Guinea
Central Manus Basin	Southwest Pacific	2,450-2,500 m	EEZ	Papua New Guinea
Conical Seamount	Southwest Pacific	1,050-1,650 m	EEZ	Papua New Guinea
Okinawa Trough	West Pacific	1,250-1,610 m	EEZ	Japan
Galapagos Rift	East Pacific	2,600-2,850 m	EEZ	Ecuador
EPR 13°N	East Pacific	2,500-2,600 m	International	
TAG	Central Atlantic	3,650-3,700 m	International	

Preussag has also performed active exploration for massive sulphide deposits in the Galapagos Spreading Centre 86°W in the mid 1980s during the GARIMAS project (Galapagos Rift Massive Sulphides), which consisted of three cruises with the German vessel SONNE. At that time it was concluded, that the Galapagos deposits are not sufficiently large and continuous to be economically mined.

It is also unlikely that deposits such as the TAG hydrothermal field, which is located in international waters at the Mid-Atlantic Ridge, the 13°N seamount at the East Pacific Rise or the Sonne hydrothermal field at the remote Rodriguez Triple Junction in the Southern Indian Ocean will become mining targets in the near future. This is also true for many of the sulphide deposits along the East, Northeast and Southeast Pacific Rises. However, in this decade, marine mining appears to be feasible under specific conditions ideally including:

- (1) high gold and base metal grades,
- (2) site location close to land, i.e., commonly within the territorial waters (200 nm Exclusive Economic Zone or even 12 nm zone) of a coastal state,
- (3) shallow water depth not significantly exceeding 2,000 m (although the technology exists for mining in deeper water,).

Under those circumstances, massive sulphide mining can be economically attractive considering that the entire mining system is portable and can be moved from mine site to mine site. An investment into mining systems and ships is thus not tied to a certain location as is the case on land, where a typical mine development in a remote area including all infrastructure requires an initial investment of US\$350-500 million.

Seafloor massive sulphide mining will likely focus on relatively small areas of the seafloor and largely be restricted to the surface (strip mining) and shallow subsurface (open cast mining) to recover sulphide mounds and chimney fields at and replacement ore bodies just below the seafloor. Environmental impact studies are yet to be carried out and will likely indicate that mining of seafloor massive sulphide deposits has only a relatively small environmental impact. For example, the high density of the sulphide particles (about 4 g/cm³) will cause immediate redeposition of any sulphide debris produced by mining equipment such as large TV-controlled hydraulic grabs or continuous mining systems with cutter heads and airlift. Due to the large surface exposed to seawater, some of the liberated sulphide debris will oxidise in a way which is not different from the oxidation of inactive massive sulphides in many of the seafloor deposits described. Acid mine drainage, which usually causes significant environmental problems in land-based sulphide mines, will not have to be considered at the seafloor due to the diluting effect of the surrounding seawater.

Sediment which could be disturbed by mining and possibly be transported by bottom currents would potentially create a major hazard to the marine ecosystem⁸³. Amos et al.⁸⁴ have pointed out that the greatest unknown and the greatest potential hazard with respect to manganese nodule mining is the behaviour and effect of sediment plumes at the seafloor, within the water column, and at the surface. While the bottom water will be directly affected by sediment disturbance due to mining equipment, the impact on the water column and the surface will be due to discharge of sediments which have been lifted along with the manganese nodules. However, a significant sediment cover is commonly not present at most seafloor sulphide deposits (except for Middle Valley and the Guaymas Basin) and thus has not to be taken into account. Consequently, mining of selected seafloor sulphide deposits, in particular those that are inactive and not inhabited by any kind of vent fauna, is feasible and does not create a larger environmental impact than the construction of a large harbour facility.

In December 1997, the Government of Papua New Guinea granted the first two marine exploration licences for seafloor sulphide deposits to an Australia-based mining company⁸⁵. The licences cover an area of about 5,000 km² in the Manus back-arc basin and include the Vienna Woods (Central Manus Basin) and the Pacmanus (Eastern Manus Basin) sites, which are located on the west side of New Ireland. Mineralisation occurs at a water depth of 2,500 m (Vienna Woods) and 1,450-1,650 m (Pacmanus). Preliminary analyses of sulphides from both deposits indicate high average gold contents (see above) along with high concentrations of base metals. However, only a limited number of

samples has been analysed so far and information about the depth extent of the mineralisation is still lacking.

A recent discovery of gold mineralisation at a seamount in a modern fore-arc environment of the Southwest Pacific suggests that a number of previously unexplored settings at the seafloor may be prospective for gold-rich hydrothermal systems. Mapping of largely uncharted waters in the Tabar-Feni island chain off Papua New Guinea revealed the position of several previously unknown volcanic cones about 10 km south of Lihir Island^{86,87}. Conical Seamount, the largest of the seamounts south of Lihir (*Fig. 5* and *Fig. 6*), is host to a new type of marine mineral deposit, characterised by extremely high concentrations of gold and a style of mineralisation that indicates the participation of gold-rich magmatic fluids (as opposed to circulating seawater) in the formation of this deposit^{71,87,88}. Samples of trachybasalt (1,200 kg) collected from the crater of Conical Seamount at a depth of 1,050 m contain up to 230 ppm Au (avg. 26 ppm, n=40, Table 5) with several dozen grains of native gold (up to 30 micron) identified as inclusions in sphalerite, galena, and amorphous silica. High concentrations of gold are uniformly associated with high concentrations of elements such as As, Sb, and Hg, known as the “epithermal suite” typical for the so-called epithermal (i.e., magmatic) gold deposits on land. The style of mineralisation is similar to that of the giant Ladolam gold deposit (1,300 tonnes Au content, daily production 60 kg Au) located on the neighbouring island of Lihir and it may be assumed that Conical Seamount represents a submarine analogue of this world-class terrestrial gold mine.

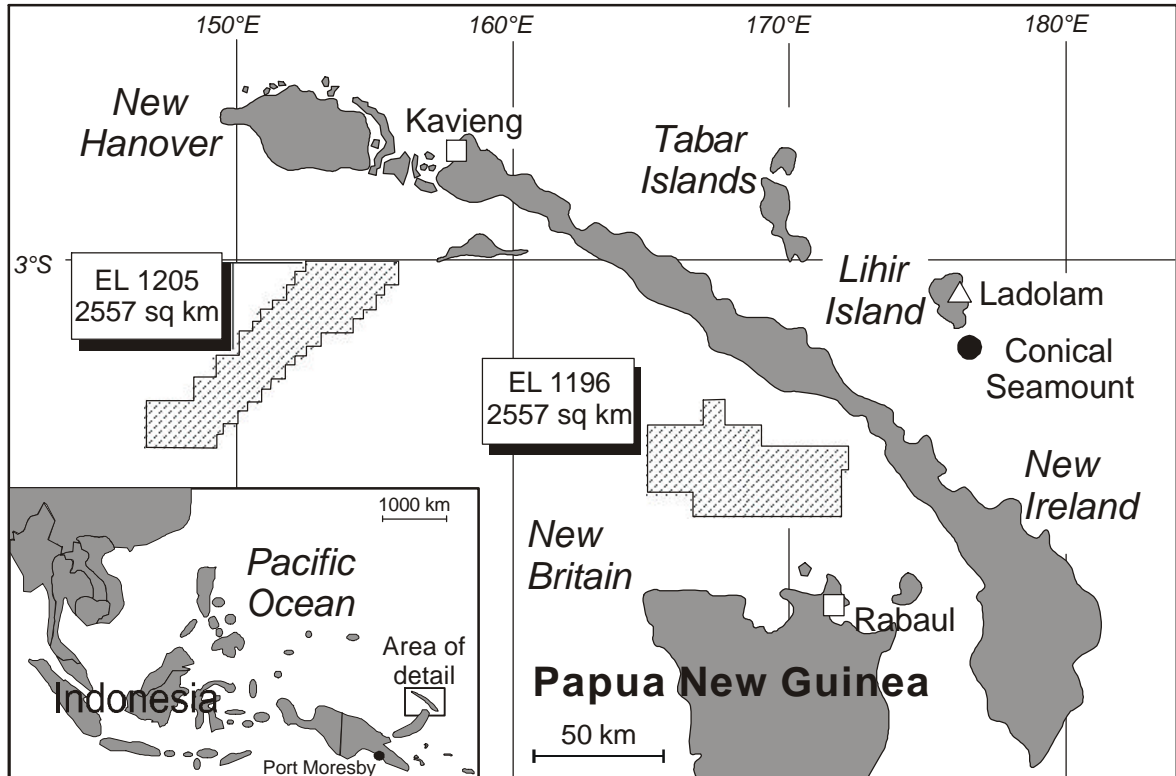


Figure 5. Map of the Manus Basin west of New Ireland showing the location of areas covered by an exploration licence granted to an Australia-based mining company by the Government of Papua New Guinea (after⁸⁵). Notice the location of Conical Seamount south of Lihir Island and the Ladolam gold deposit on Lihir Island.

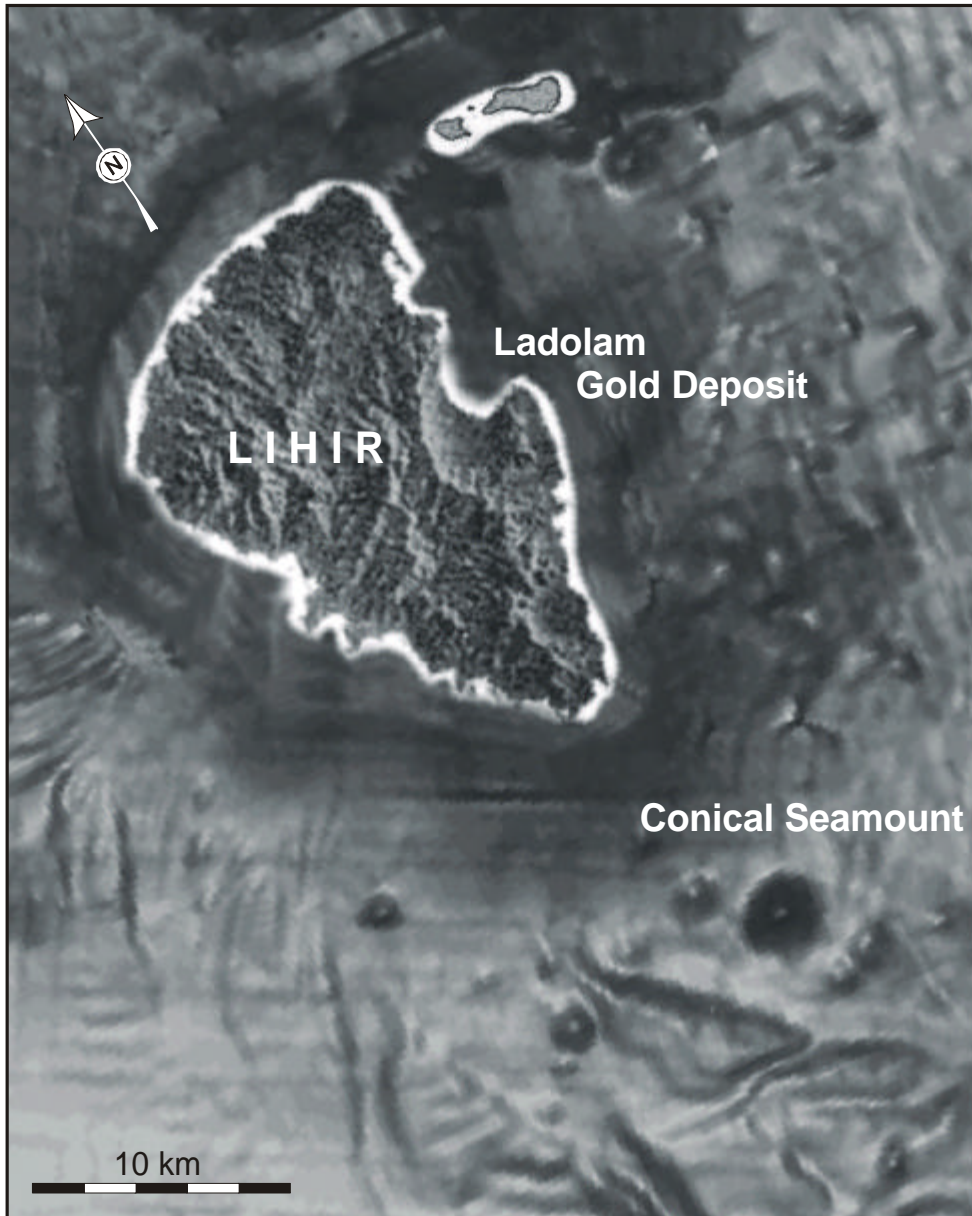


Figure 6. Bathymetry-based shaded relief of the Lihir Island group with the location of volcanic cones south of Lihir including Conical Seamount, which is host to a new type of submarine gold mineralisation.

9. PERSPECTIVE

If further exploration through drilling proves that high-grade gold mineralisation is widespread and abundant, Conical Seamount may become the first marine gold deposit to be mined. In addition to high concentrations of gold, the advantages of this site include shallow water depth (1,050 m) and the location within the 12 nm zone of Papua New Guinea. Furthermore, the deposit is inactive (no disturbance of fauna) and almost sediment-free (no plume development due to mining activities). Processing of the gold ore could take place in the 25 km distant Ladolam gold processing plant on Lihir. If this scenario becomes reality, it will have a very significant impact on the future development of seafloor mining for base and precious metals. Given the known distribution of potentially minable sulphide deposits on the seafloor, it is very likely that most future development of sulphide mining will take place in national rather than international waters.

Considering all critical factors, mining of seafloor polymetallic massive sulphide deposits is likely to take place in the current decade. In this context it should be remembered, that only about 35 years ago, the oil industry went off shore and there is no doubt that this was a very successful endeavour. Today, the international mining industry is about to follow ...

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11. REFERENCES

1. J. Francheteau, H.D. Needham, P. Choukroune, T. Juteau, M. Seguret, R.D. Ballard, P.J. Fox, W. Normark, A. Carranza, D. Cordoba, J. Guerrero, C. Rangin, H. Bougault, P. Cambon, and R. Hekinian (1979), Massive deep-sea sulphide ore deposits discovered on the East Pacific Rise. *Nature*, 277, 523-528.
2. F.N. Spiess, K.C. Macdonald, T. Atwater, R. Ballard, A. Carranza, D. Cordoba, C. Cox, V.M. Diaz Garcia, J. Francheteau, J. Guerrero, J.W. Hawkins, R. Haymon, R. Hessler, T. Juteau, M. Kastner, R. Larson, B. Luyendyk, J.D. Macdougall, S. Miller, W. Normark, J. Orcutt, C. Rangin (1980), East Pacific Rise. Hot springs and geophysical experiments. *Science*, 207, 1421-1433.

3. J.M. Franklin, J.W. Lydon, and D.F. Sangster (1981), Volcanic-associated massive sulphide deposits. *Economic Geology, 75th Anniversary Volume*, 485-627.
4. S.D. Scott (1985), Seafloor polymetallic sulphide deposits: Modern and ancient. *Marine Mining*, 5, 191-212.
5. J.M. Franklin (1986), Volcanic associated massive sulphide deposits - an update. In: *Geology and Genesis of Mineral Deposits in Ireland*, C.J. Andrew et al. (eds.), Irish Association for Economic Geology, 49-70.
6. R.A. Koski (1987) Sulphide deposits on the seafloor: geological models and resource perspectives based on studies in ophiolite sequences. In: *Marine Minerals: Resource Assessment Strategies*, P.G. Teleki et al. (eds.), *Proceedings NATO Advanced Research Workshop, Series C*, 194, Reidel Publishing Boston, 301-316.
7. S.D. Scott (1987) Seafloor polymetallic sulphides: Scientific curiosities or mines of the future? In: *Marine Minerals: Resource Assessment Strategies*, P.G. Teleki et al. (eds.), *Proceedings NATO Advanced Research Workshop, Series C*, 194, Reidel Publishing Boston, 277-300.
8. P.M. Herzig, and M.D. Hannington (1995), Polymetallic massive sulphides at the modern seafloor - A review. *Ore Geology Review*, 10, 95-115.
9. P.A. Rona, G. Klinkhammer, T.A. Nelsen, J.H. Trefry, and H. Elderfield (1986), Black smokers, massive sulphides and vent biota at the Mid-Atlantic Ridge. *Nature*, 321, 33-37.
10. S.G. Krasnov, G.A. Cherkashev, T.V. Stepanova, B.N. Batuyev, A.G. Krotov, B.V. Malin, M.N. Maslov, V.F. Markov, I.M. Poroshina, M.S. Samovarov, A.M. Ashadze, and I.K. Ermolayev (1995), Detailed geographical studies of hydrothermal fields in the North Atlantic. In: *Hydrothermal Vents and Processes, Geological Society Special Publication*, L.M. Parson, C.L. Walker, D.R. Dixon (eds.), 87, 43-64.
11. L.S.L. Kong, W.B.F. Ryan, L. Mayer, R. Detrick, P.J. Fox, and K. Manchester (1985), Bare-rock drill site: ODP legs 106 and 109: evidence for hydrothermal activity at 23°N on the Mid-Atlantic Ridge. *American Geophysical Union Transactions*, 66, 936.
12. B.J. Murton, C. Van Dover, and E. Southward (1995), Geological setting and ecology of the Broken Spur hydrothermal vent field: 29°10'N on the Mid-Atlantic Ridge. In: *Hydrothermal Vents and Processes, Geological Society Special Publication*, L.M. Parson, C.L. Walker, D.R. Dixon (eds.), 87, 33-41.
13. Y. Fouquet, J.L. Charlou, I. Costa, J.P. Donval, J. Radford-Knoery, H. Pelle, H. Ondreas, N. Lourenco, M. Segonzac, and M. Tivey (1994), A detailed study of the Lucky Strike hydrothermal site and discovery of a new hydrothermal site: Menez Gwen; preliminary results of the DIVA 1 cruise. *InterRidge News*, 3, 2, 14-17.
14. P.M. Herzig and W.L. Plüger (1988), Exploration for hydrothermal mineralization near the Rodriguez Triple Junction, Indian Ocean. *Canadian Mineralogist*, 26: 721-736.

15. W.L. Plüger, P.M. Herzig, K.-P. Becker, G. Deissmann, D. Schöps, J. Lange, A. Jenisch, S. Ladage, H.H. Richnow, T. Schulze, and W. Michaelis (1990), Discovery of hydrothermal fields at the Central Indian Ridge. *Marine Mining*, 9, 73-86
16. P. Halbach, N. Blum, U. Münch, W.L. Plüger, D. Garbe-Schönberg, and M. Zimmer (1998), Formation and decay of a modern massive sulphide deposit in the Indian Ocean. *Mineralium Deposita*, 33, 302-309
17. P. Lonsdale, J.L. Bischoff, V.M. Burns, M. Kastner, and R.E. Sweeney (1980), A high-temperature hydrothermal deposit on the seabed at a Gulf of California spreading centre. *Earth and Planetary Science Letters*, 49, 8-20.
18. M.J. Mottl, E. Davis, A.T. Fisher (1991) (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, 139, College Station, TX.
19. R.A. Zierenberg, Y. Fouquet, D.J. Miller and Leg 169 shipboard scientific party (1996), The roots of seafloor sulphide deposits: preliminary results from ODP Leg 169 drilling in Middle Valley and Escanaba Trough. *American Geophysical Union Transactions*, 77: 765.
20. R.A. Both, K. Crook, B. Taylor, S. Brogan, B. Chapell, E. Frankel, L. Liu, J. Sinton and D. Tiffin (1986), Hydrothermal chimneys and associated fauna in the Manus back-arc basin, Papua New Guinea *American Geophysical Union Transactions*, 67, 489-490.
21. H. Craig, Y. Horibe, K.A. Farley, J.A. Welhan, K.R. Kim, R.N. Hey (1987), Hydrothermal vents in the Mariana Trough: Results of the first Alvin dives. *American Geophysical Union Transactions*, 68, 1531.
22. M. Kastner, H. Craig, A. Sturz (1987), Hydrothermal deposition in the Mariana Trough: Preliminary mineralogical investigations. *American Geophysical Union Transactions*, 68: 1531.
23. J.M. Auzende, T. Urabe, C. Deplus, J.P. Eissen, D. Grimaud, P. Huchon, J. Ishibashi M. Joshima, Y. Lagabriele, C. Mevel, J. Naka, E. Ruellan, T. Tanaka, M. Tanahashi (1989), Le cadre geologique d' un site hydrothermal actif. la campagne Starmer 1 du submersible nautille dans le Bassin Nord Fidjien. *C.R. Acad. Sci. Paris*, 309, 1787-1795.
24. Y. Fouquet, U. Von Stackelberg, J.L. Charlou, J.L. Donval, J. Erzinger, J.P. Foucher, P.M. Herzig, R. Mühe, S. Soakai, M. Wiedicke, and H. Whitechurch (1991), Hydrothermal activity and metallogenesis in the Lau back-arc basin. *Nature*, 349, 778-781.
25. P. Halbach, K. Nakamura, M. Wahsner, J. Lange, H. Sakai, L. Käseltz, R.D. Hansen, M. Yamano, J. Post, B. Prause, R. Seifert, W. Michaelis, F. Teichmann, M. Kinoshita, A. Märten, J. Ishibashi, S. Czerwinski, N. Blum (1989), Probable modern analogue of Kuroko-type massive sulphide deposits in the Okinawa Trough back-arc basin. *Nature*, 338, 496-499.

26. R.A. Binns, and S.D. Scott (1993), Actively forming polymetallic sulphide deposits associated with felsic volcanic rocks in the Eastern Manus back-arc basin, Papua New Guinea. *Economic Geology*, 88, 2226-2236.
27. R.A. Binns, and D.J. Whitford (1987), Volcanic rocks from the western Woodlark Basin, Papua New Guinea. *Australasian Institute of Mining and Metallurgy, Pacific Rim Conference*, 1, 525-531.
28. P.A. Rona (1988), Hydrothermal mineralisation at oceanic ridges. *Canadian Mineralogist*, 26, 431-465.
29. P.A. Rona, and S.D. Scott (1993), Preface to Special Issue on sea-floor hydrothermal mineralisation: new Perspectives. *Economic Geology*, 88, 1935-1976.
30. M.D. Hannington, S. Petersen, I.R. Jonasson, and J.M. Franklin (1994), Hydrothermal activity and associated mineral deposits on the seafloor. *Geological Survey of Canada Open File Report, 2915C, Map 1:35,000,000 and CD-ROM*.
31. C.J. Richardson, J.R. Cann, H.G. Richards, J.G. Cowan (1987), Metal-depleted root zones of the Troodos ore-forming hydrothermal system, Cyprus. *Earth and Planetary Science Letters*, 84: 243-253.
32. D. Schöps, and P.M. Herzig (1990), Sulphide composition and microthermometry of fluid inclusions in quartz-sulphide veins from the leg 111 dike section of ODP Hole 504B, Costa Rica Rift. *Journal of Geophysical Research*, 95, 8405-8418.
33. J.R. Cann, M.R. Strens (1982), Black smokers fuelled by freezing magma. *Nature*, 298: 147-149.
34. R.S.P. Detrick, E. Buhl, J. Vera, J. Mutter, J. Orcutt, J. Madsen, T. Brocher (1987), Multi-channel seismic imaging of a crustal magma chamber along the East Pacific Rise. *Nature*, 326, 35-41.
35. J. Collier, M. Sinha (1990), Seismic images of a magma chamber beneath the Lau Basin back-arc spreading centre. *Nature*, 346, 646-648.
36. D. Kadko, W. Moore (1988), Radiochemical constraints on the crustal residence time of submarine hydrothermal fluids: Endeavour Ridge. *Geochimica et Cosmochimica Acta*, 52, 659-668.
37. A. Hajash (1975), Hydrothermal processes along Mid-Ocean Ridges: an experimental investigation. *Contributions in Mineralogy and Petrology*, 53, 205-226.
38. W.E. (jr.) Seyfried, M.J. Mottl (1982), Hydrothermal alteration of basalt by seawater under seawater-dominated conditions. *Geochimica et Cosmochimica Acta*, 46, 985-1002.
39. W.E. (jr.) Seyfried, M.E. Berndt, J.S. Seewald (1988), Hydrothermal alteration processes at mid-ocean ridges: constraints from diabase alteration experiments, hot-spring fluids and composition of the oceanic crust. *Canadian Mineralogist*, 26, 787-804.

40. J.C. Alt (1995), Sub-seafloor processes in mid-ocean ridge hydrothermal systems. In: Humphris S.E., et al. (eds.) *Seafloor Hydrothermal Systems: Physical, Chemical, Biological and Geological Interactions*. *AGU Geophysical Monograph*, 91, 85-114.
41. Y. Fouquet, U. von Stackelberg, J.L. Charlou, J. Erzinger, P.M. Herzig, R. Mühe, M. Wiedicke (1993), Metallogenesis in back-arc environments: the Lau Basin example. *Economic Geology*, 88, 2154-2181.
42. K.L. Von Damm (1995), Controls on the chemistry and temporal variability of seafloor hydrothermal fluids. In: *Seafloor Hydrothermal Systems: Physical, Chemical, Biological and Geological Interactions*, Humphris, S.E. et al. (eds.), *AGU Geophysical Monograph*, 91, 222-247.
43. M.J. Mottl (1983), Metabasalts, axial hot-springs, and the structure of hydrothermal systems at mid-ocean ridges. *Geological Society of America Bulletin*, 94, 161-180.
44. R.R. Keays (1987), Principles of mobilisation (dissolution) of metals in mafic and ultramafic rocks - The role of immiscible magmatic sulphides in the generation of hydrothermal gold and volcanogenic massive sulphide deposits. *Ore Geology Reviews*, 2, 47-63.
45. R.M. Haymon, and M. Kastner (1981), Hot spring deposits on the East Pacific Rise at 21°N: preliminary description of mineralogy and genesis. *Earth and Planetary Science Letters*, 53, 363-381.
46. M.S. Goldfarb, D.R. Converse, H.D. Holland, and J.M. Edmond (1983), The genesis of hot spring deposits on the East Pacific Rise, 21°N. *Economic Geology Monograph* 5, 184-197.
47. R.M. Haymon (1983), Growth history of hydrothermal black smoker chimneys. *Nature*, 301, 695-698.
48. E. Oudin (1983), Hydrothermal sulphide deposits of the East Pacific Rise (21°N) part I: descriptive mineralogy. *Marine Mining*, 4, 39-72.
49. R. A. Koski, D.A. Clague, and E. Oudin (1984), Mineralogy and chemistry of massive sulphide deposits from the Juan de Fuca Ridge. *Geological Society of America Bulletin*, 95, 930-945.
50. Y. Fouquet, G. Auclair, P. Cambon, and J. Etoubleau (1988), Geological setting, mineralogical and geochemical investigations on sulphide deposits near 13°N on the East Pacific Rise. *Marine Geology*, 84, 145-178.
51. Hannington, M.D., Herzig, P.M., Scott, S.D., Thompson, G., and Rona, P.A. (1991). Comparative mineralogy and geochemistry of gold-bearing sulphide deposits on the mid-ocean ridges. *Marine Geology*, 101, 217-248.
52. Y. Fouquet, U. von Stackelberg, J.L. Charlou, J. Erzinger, P.M. Herzig, R. Mühe, and M. Wiedicke (1993), Metallogenesis in back-arc environments: the Lau Basin example. *Economic Geology*, 88, 2154-2181.

53. P.M. Herzig, Y. Fouquet, M.D. Hannington, U. Von Stackelberg (1990), Visible gold in primary polymetallic sulphides from the Lau back-arc. *American Geophysical Union Transactions*, 71, 1680.
54. P.M. Herzig, M.D. Hannington, Y. Fouquet, U. Von Stackelberg, and S. Petersen (1993), Gold-rich polymetallic sulphides from the Lau back-arc and implications for the geochemistry of gold in sea-floor hydrothermal systems of the Southwest Pacific. *Economic Geology*, 88, 2182-2209.
55. P.M. Herzig, S.E. Humphris, D.J. Miller, and R.A. Zierenberg (eds.) (1998) *Proceedings of the Ocean Drilling Program, Scientific Results*, 158, College Station, TX, 427 p.
56. R.A. Zierenberg, Y. Fouquet, D.J. Miller, J.M. Bahr, P.A. Baker, T. Bjerkgaard, C.A. Brunner, R.C. Duckworth, R. Gable, J. Gieskes, W.D. Goodfellow, H.M. Gröschel-Becker, G. Guerin, J. Ishibashi, G. Iturrino, R.H. James, K.S. Lackschewitz, L.L. Marquez, P. Nehlig, J.M. Peter, C. A. Rigsby, P. Schultheiss, W.C. Shanks III, B.R.T. Simoneit, M. Summit, D.A.H. Teagle, M. Urbat, and G.G. Zuffa (1998). The deep structure of a sea-floor hydrothermal deposit. *Nature*, 392, 485-488.
57. T.S. Bowers, A.C. Campbell, C.I. Measures, A.J. Spivack, and J.M. Edmond (1988), Chemical controls on the composition of vent fluids at 13°N-11°N and 21°N, East Pacific Rise. *Journal of Geophysical Research*, 93, 4522-4536.
58. A.C. Campbell, T.S. Bowers, and J.M. Edmond (1988), A time-series of vent fluid composition from 21°N, EPR (1979, 1981, 1985) and the Guaymas Basin, Gulf of California (1982, 1985). *Journal of Geophysical Research*, 93, 4537-4549.
59. K.L. Von Damm (1988), Systematics of and postulated controls on submarine hydrothermal solution chemistry. *Journal of Geophysical Research*, 93, 4551-4561.
60. H. Ohmoto, and B.J. Skinner (1983), (eds), The Kuroko and related volcanogenic massive sulphide deposits. *Economic Geology Monograph* 5: 604.
61. S.E. Humphris, P.M. Herzig, D.J. Miller, J.C. Alt, K. Beckert, D. Brown, G. Brügmann, H. Chiba, Y. Fouquet, J.B. Gemmell, G. Guerin, M.D. Hannington, N.G. Holm, J.J. Honnorez, G.J. Itturino, R. Knott, R. Ludwig, K. Nakamura, S. Petersen, A.-L. Reysenbach, P.A. Rona, S. Smith, A.A. Sturz, M.K. Tivey, and X. Zhao (1995), The internal structure of an active sea-floor massive sulphide deposit. *Nature*, 377, 713-716.
62. M. Hannington, A.G. Galley, P.M. Herzig, and S. Petersen (1998). Comparison of the TAG mound and stockwork complex with Cyprus-type massive sulphide deposits. In, *Proc. ODP, Sci. Results*, Herzig, P.M., Humphris, S.E., Miller, J., and Zierenberg, R.A. (eds) College Station, TX 158, 389-415.
63. E.T. Degens, and D.A. Ross (1969), *Hot brines and recent heavy metal deposits in the Red Sea*. Springer Verlag, New York, 600 p.
64. Z.A. Nawab (1984), Red sea mining: a new era. *Deep Sea Research* 31, 813-822.

65. H.E. Mustafa, Z. Nawab, R. Horn, and F. Le Mann (1984), Economic interest of hydrothermal deposits: Atlantis II project, In: *Proceedings of 2nd International Seminar on Offshore Mineral Resources, Brest, France*, 509-539.
66. E. Oudin (1987), Trace elements and precious metal concentrations in East Pacific Rise, Cyprus and Red Sea submarine sulphides: In: *Marine Minerals: Advances in Research and Resource Assessment strategies. Proceedings of the NATO Advanced Research Workshop, Series C*, Teleki, P.G., Dobson, M.R., Moore, J.R., and Stackelberg, U. (eds) 194, 349-362.
67. S.D. Scott, R.L. Chase, M.D. Hannington, P.J. Michael, and T.F. McConachy (1990), Sulphide deposits, tectonics and petrogenesis of Explorer Ridge, Northeast Pacific Ocean. In, *Troodos '87*. Malpas, J., Moores, E.M., Panayiotou, A., and Xenophontos, C. (eds), Geological Survey Department, Nicosia, Cyprus: 719-733.
68. M.D. Hannington, J.M. Peter, and S.D. Scott (1986), Gold in seafloor polymetallic sulphide deposits. *Economic Geology*, 81, 1867-1883.
69. M.D. Hannington, and S.D. Scott (1988), Gold and silver potential of polymetallic sulphide deposits on the sea floor. *Marine Mining*, 7: 271-285.
70. M.D. Hannington, and S.D. Scott (1989), Gold mineralisation in volcanogenic massive sulphides: implications of data from active hydrothermal vents on the modern sea floor. *Economic Geology Monograph* ,: 491-507.
71. M.D. Hannington, M.K. Tivey, A.C. Larocque, S. Petersen, and P.A. Rona, (1995) The occurrence of gold in sulphide deposits of the TAG hydrothermal field, Mid-Atlantic Ridge. *Canadian Mineralogist*, 33, 1285-1310.
72. R.A. Koski, W.C. Shanks III., W.A. Bohrsen, and R.L. Oscarson (1988), The composition of massive sulphide deposits from the sediment-covered floor of Escanaba Trough, Gorda Ridge: implications for depositional processes. *Canadian Mineralogist*, 26, 655-673.
73. R.A. Zierenberg, and P. Schiffman (1990), Microbial control of silver mineralisation at a sea-floor hydrothermal site on the northern Gorda Ridge. *Nature* 348:155-157.
74. P. Halbach, B. Pracejus, and A. Märten (1993), Geology and mineralogy of massive sulphide ores from the Central Okinawa Trough, Japan. *Economic Geology*, 88, 2210-2225.
75. T. Urabe, K. Marumo, and K. Nakamura (1990), Mineralisation and related hydrothermal alteration in Izena cauldron (JADE site), Okinawa Trough, Japan. *Geological Society of America Abstracts with Programs*, 22, A9.
76. R.A. Binns (1994), Submarine deposits of base and precious metals in Papua New Guinea. In: *Proceedings PNG Geology, Exploration and Mining Conference 1994*, Rogerson, R. (ed.), The Australasian Institute of Mining and Metallurgy, 71-83.

77. R.A. Binns, T. Boyd, and S.D. Scott (1991), Precious metal spires from the Western Woodlark Basin, Papua New Guinea. *Geological Association of Canada Program with Abstracts*, 16, A12.
78. R.A. Binns, S.D. Scott, Y.A. Bogdanov, A.P. Lisitsin, V.V. Gordeev, E.J. Finlayson, T. Boyd, L.E. Dotter, G.E. Wheller, and K.G. Muravyev (1993), Hydrothermal oxide and gold-rich sulfate deposits of Franklin Seamount, western Woodlark Basin, Papua New Guinea. *Economic Geology*, 88, 2122-2153.
79. P.M. Herzig, S. Petersen, M.D. Hannington, and I.R. Jonasson (2000) Conical Seamount: A Submarine Analog of the Ladolam Epithermal Gold Deposit on Lihir Island, Papua New Guinea? (*submitted*)
80. S. Petersen, P.M. Herzig, M.D. Hannington, and I.R. Jonasson (in prep), Submarine epithermal-style gold mineralization near Lihir Island, New Ireland fore arc, Papua New Guinea.
81. H. Amann (1985), Development of ocean mining in the Red Sea. *Marine Mining*, 5, 163-172.
82. H. Amann (1989), The Red Sea Pilot Project: Lessons for future ocean mining. *Marine Mining*, 8, 1-22.
83. J. Schneider, and H. Thiel (1988), Environmental problems of deep-sea mining, In: *The Manganese Nodule Belt of the Pacific Ocean*, Halbach, P., Friedrich, G., and von Stackelberg, U. (eds), 222-228.
84. A.F. Amos, O.A. Roels, C. Garside, T.C. Malone, and A.Z. Paul (1977), Environmental aspects of nodule mining, In: *Marine Manganese Deposits*, Elsevier Oceanographic Series, 15, Glasby, G.P. (ed), Amsterdam, 391-437.
85. The New York Times (1997), First move made to mine mineral riches of seabed (William J. Broad), December 21, 1997.
86. P.M. Herzig, M.D. Hannington, B. McInnes, P. Stoffers, H. Villinger, R. Seifert, R. Binns, T. Liebe, and Scientific Party (1994), Submarine alkaline volcanism and active hydrothermal venting in the New Ireland forearc basin, Papua New Guinea. *Transactions of the American Geophysical Union*, 75, 513-516.
87. P.M. Herzig, and M.D. Hannington (1995), Hydrothermal activity, vent fauna, and submarine gold mineralisation at alkaline fore-arc seamounts near Lihir Island, Papua New Guinea. *Proceedings Pacific Rim Congress 1995, Australasian Institute of Mining and Metallurgy*, 279-284.
88. P.M. Herzig, S. Petersen and M.D. Hannington (1999), Epithermal-type gold mineralisation at Conical Seamount: a shallow submarine volcano south of Lihir Island, Papua New Guinea. In: *Mineral Deposits: Processes to Processing, Proceedings of the fifth biennial SGA meeting and the tenth Quadrennial IAGOD symposium London*: Stanley C.J. et al 527-530.